Enabling Efficient Human Multi-Tasking

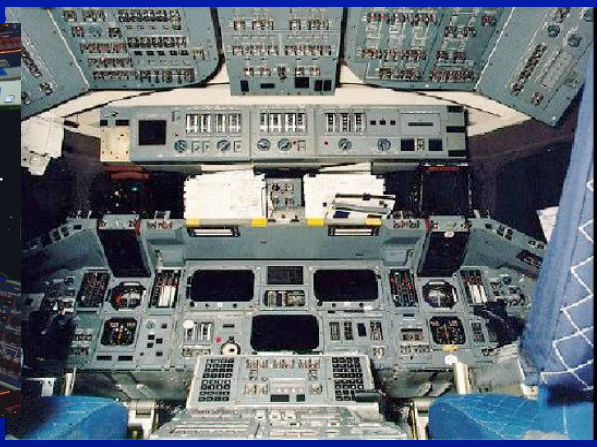
Eric Ruthruff

NASA Ames Research Center

Collaborators

Roger W. Remington
James C. Johnston
Eliot Hazeltine
Mei-Ching Lien
Joel Lachter
Mark Van Selst

Human Multi-Tasking



- Human operators in domains critical to NASA often must deal with more than one time-critical task
  - Pilots
  - Controllers
  - Astronauts
- Unfortunately, human multi-tasking skills are known to be severely limited

Human Multi-Tasking

- Multi-tasking problems occur because…
  - It is difficult to switch between tasks
  - It is difficult to perform multiple tasks at the same time
- These processing limitations constrain throughput and can lead to human error, risking catastrophic consequences in NASA environments
- It may be possible to improve human multi-tasking if we can better understand human limitations

Multi-Task Research in the Cognition Lab

- Task switching (4 papers)
  - Significant contributions to theories of task switching
  - Findings reflected in human performance models
- Dual-task interference (over 40 papers)
  - Developed a bottleneck theory of dual-task performance
  - Bottleneck theory is the foundation for determining resource constraints in human performance models

Research Rationale

- Goal: Enable more efficient human multi-tasking
  - Mitigate human error
  - Improve throughput
  - Reduce workload
- Approach:
  - Understand underlying causes of dual-task interference
  - Different causes suggest different remedies
    - Changing the people to suit the tasks
      - Instruction
      - Motivation
      - Practice
    - Changing the tasks to suit the people

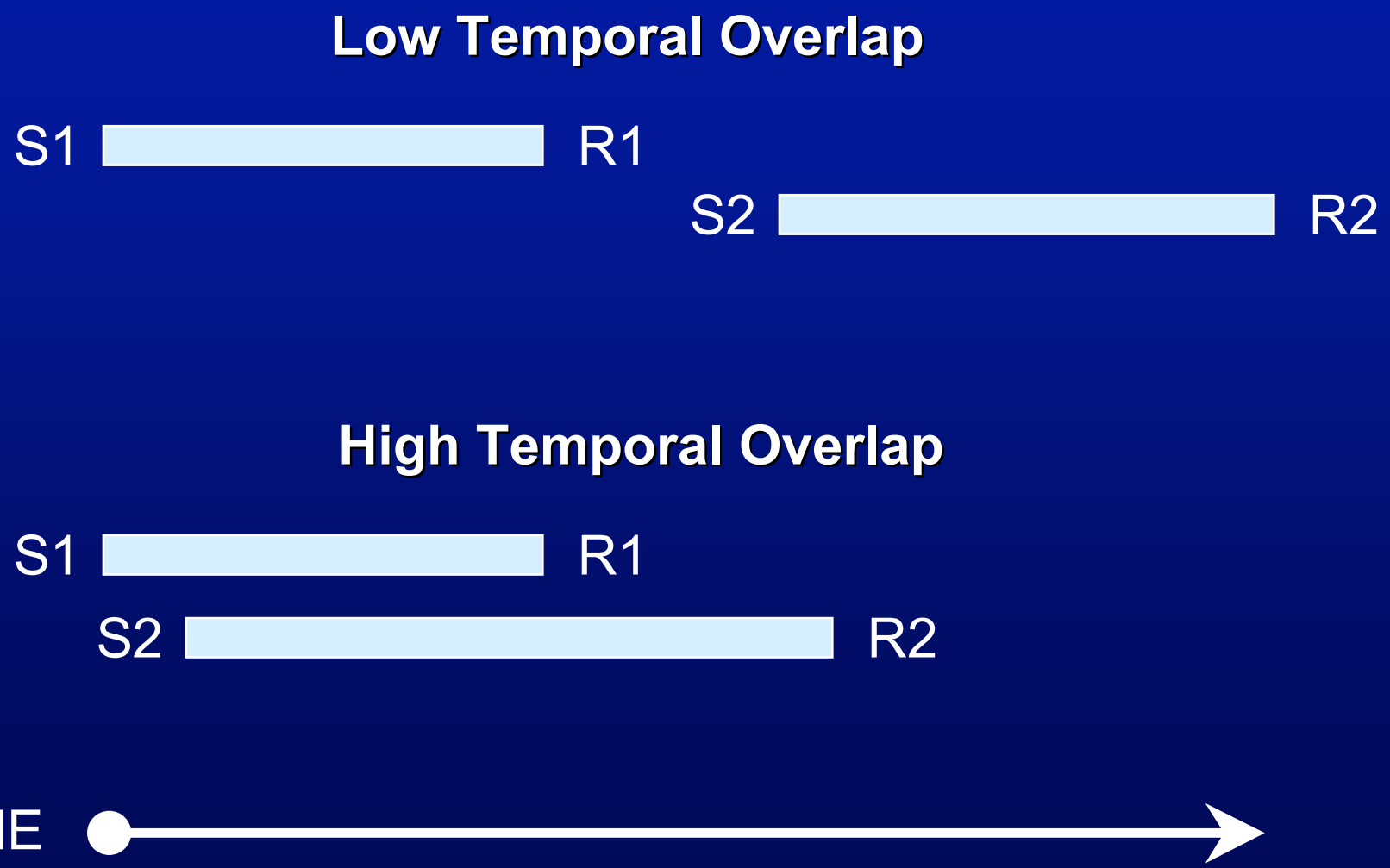
What kind of studies?

- Realistic simulation of some real-world domain (ATC)
  - High face validity, but…
  - Costly
  - Complex
  - Difficult to determine reasons for performance successes and failures
- Fundamental research with generic cognitive tasks
  - Easier to determine which cognitive components are responsible for performance successes and failures
  - Easier to develop and test fundamental models of cognition that are generalizable across domains (cross-cutting)

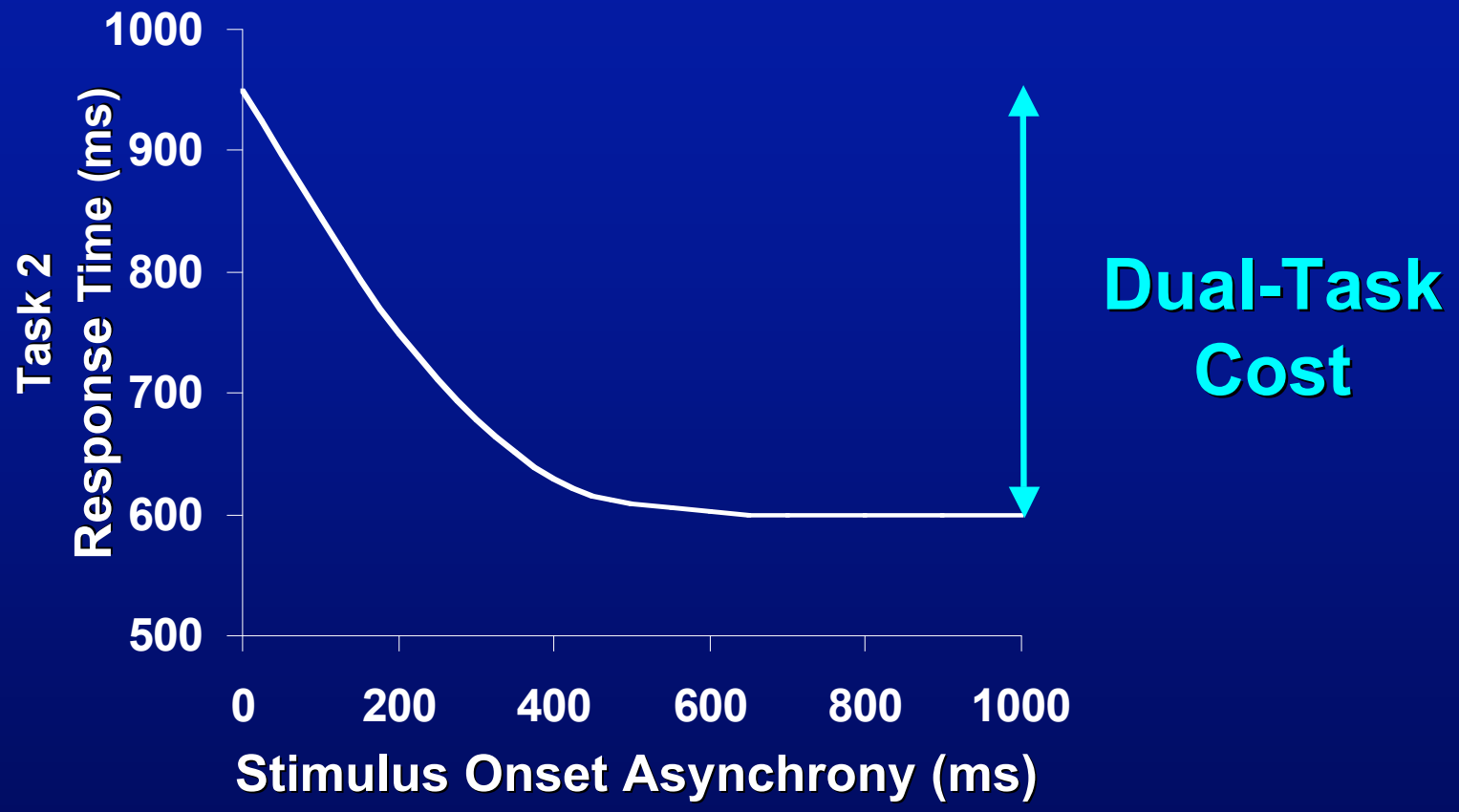
Basic Questions

- What happens when a person is given two simple cognitive tasks at the same time?
- Does interference occur? How much? Under what conditions?

Dual-Task Methodology



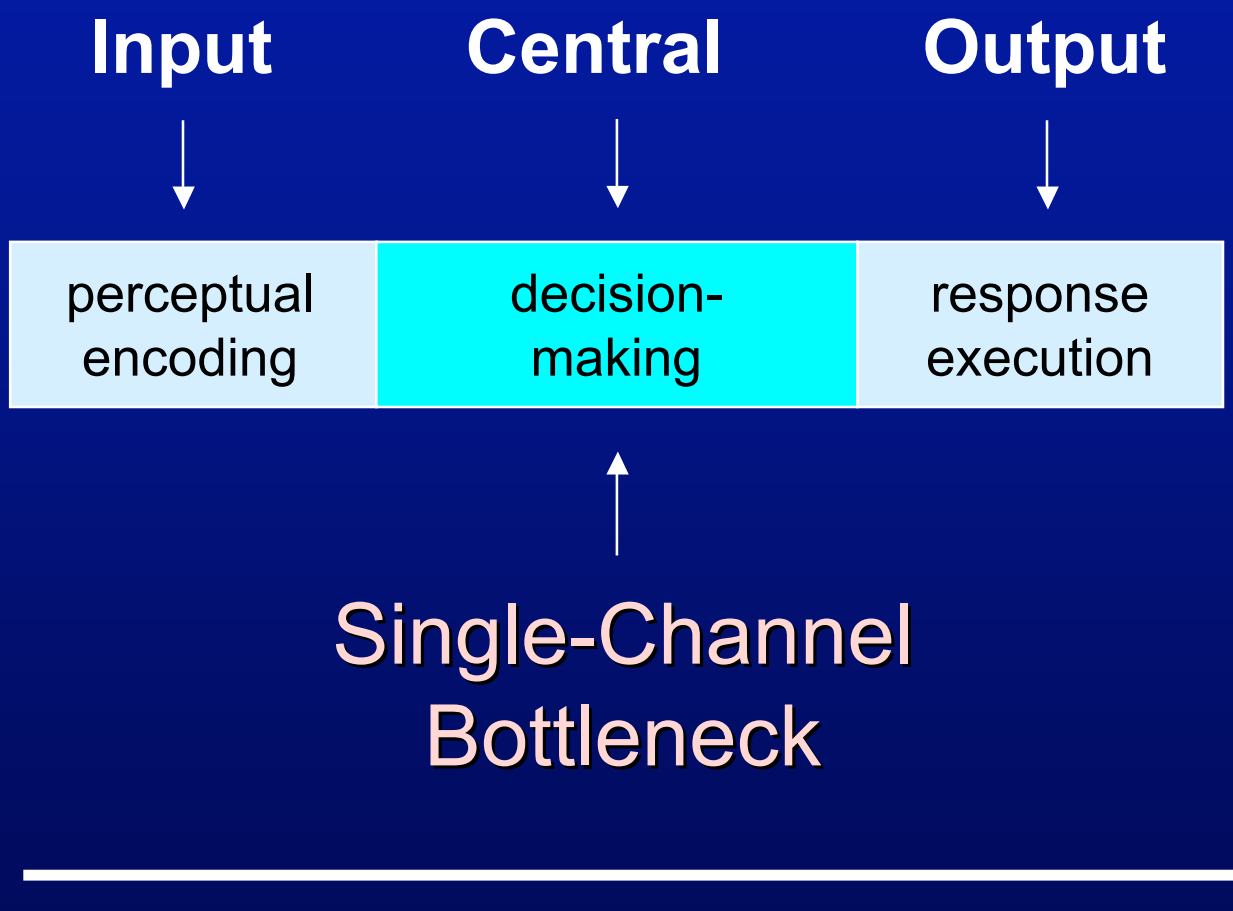
Dual-Task Interference



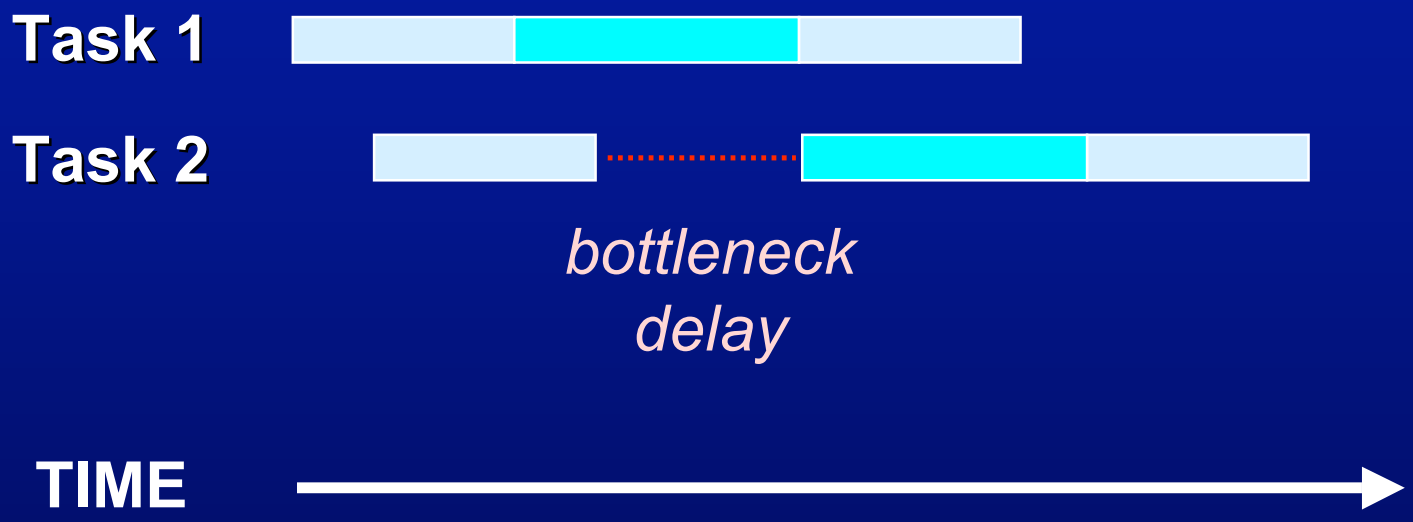
Dual-Task Costs

- Dual-task costs can be large
  - Second task slowed by 50%
  - Even with no conflicts between input modalities or between output modalities
  - Even with very simple tasks
- What are the underlying causes?

Central Bottleneck Model



Central Bottleneck Model



Nature of the Central Bottleneck

- Which processes are subject to the bottleneck?
  - Response selection (McCann & Johnston, 1992)
  - Mental rotation (Ruthruff, Miller, & Lachmann, 1995)
  - Memory retrieval (Carrier & Pashler, 1994)
  - Stimulus classification (Johnston & McCann, in press)
- Evidence that none of these operations can overlap with any other (like the CPU of a computer)
  - Somewhat surprising given the architecture of the brain
  - No evidence for a “CPU” in the brain
- Case Study: Driving while talking on a cell phone
  - Do “hands-free” cell phones eliminate interference?
  - Our bottleneck model says “no”

Dual-task Remedies

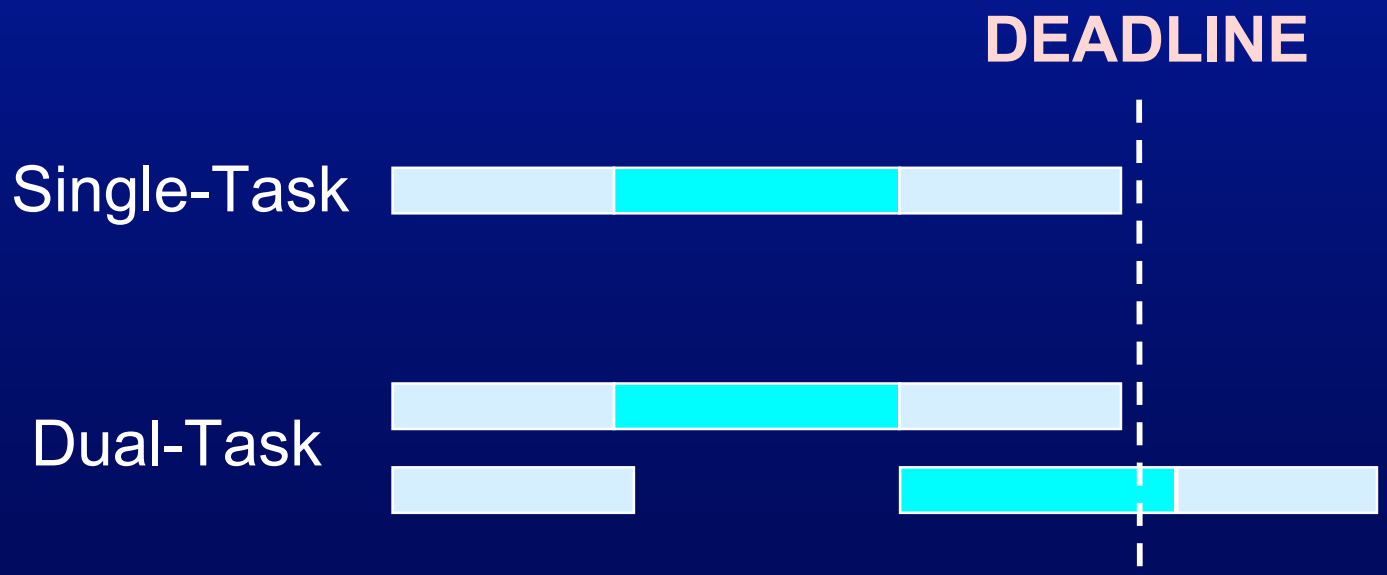
- How can the central bottleneck be eliminated?
- If not eliminated, how can it be ameliorated?
- We have pursued three promising avenues
  - Increasing motivation
  - Providing extensive practice
  - Improving task design

Part I: Motivation

- Strategic Bottleneck Hypothesis: People can do two tasks at once, but choose not to
  - The central bottleneck could be avoided with greater effort
  - Plausible because in previous studies slow responses were not penalized (no negative feedback)
- To test this hypothesis, we created a novel dual-task paradigm
  - Success virtually requires people to do two tasks at once
  - Slow responses penalized w/ immediate negative feedback

Incentives for Parallel Central Processing

- Approach: Set firm time deadlines
  - Same deadline for single and dual-task blocks
  - No extra time allowed on dual-task trials



- **Must overlap central processes, or fail**

Deadlines with a New Twist

- Traditional method: Present a separate signal (e.g., a tone) when deadline time is up
  - Monitoring for deadline signal creates extra task
  - Difficult to measure progress toward deadline time
- New method: Use tasks with inherent time deadlines
  - Catching a ball thrown at you
  - No affordance for late responses (must catch ball before it passes you)
  - Explicit feedback that late responses constitute failure

Method

- Two tasks
  - Shape task
    - See one of three shapes
    - Press assigned key

  - Tone task
    - Hear one of three tones (low, medium, high)
    - Say “one”, “two”, “three”

- Two types of blocks
  - Single-task
  - Dual-task

Dependent Measure

- Primary dependent measure is **success rate**
  - Success = Correct response and in time
  - Joint dual-task success = Both responses correct and in time
- Question: Will dual-task interference still occur? Or will participants rise to the challenge and find a way to do both tasks at the same time?

Results (N=24)

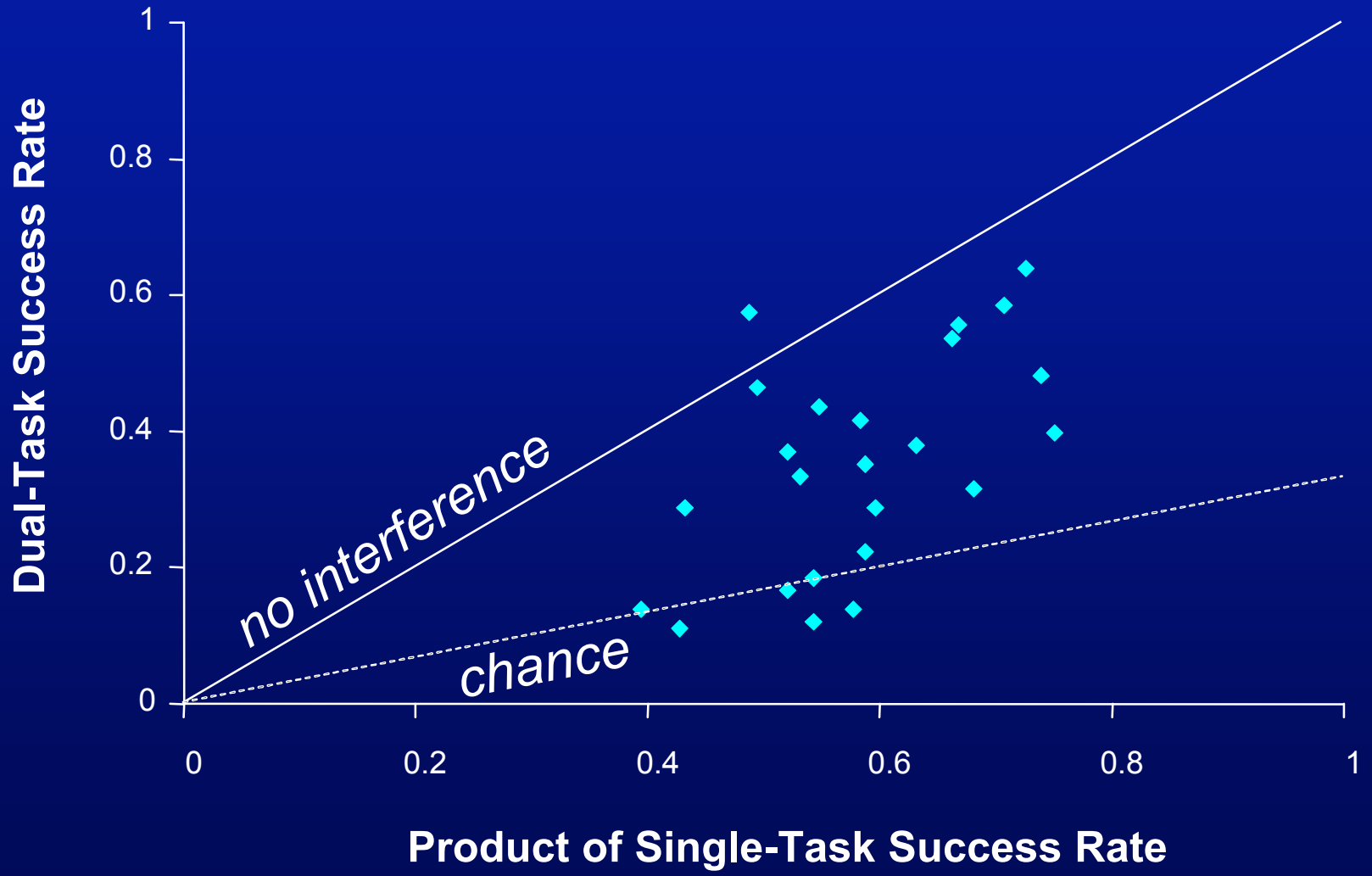
Joint dual-task success (both tasks correct & in time):

Predicted = **.58** (assuming no interference)

Actual = **.35**

Cost = **.23**

Dual-Task Success Rate



Findings

- Dual-task interference occurred even with…
  - Easy tasks
  - Strong incentives to avoid the central bottleneck
- No evidence that the central bottleneck can be bypassed simply by exerting more effort
- Results replicate even with easier tasks and a more “game-like” scenario

Part II: Practice

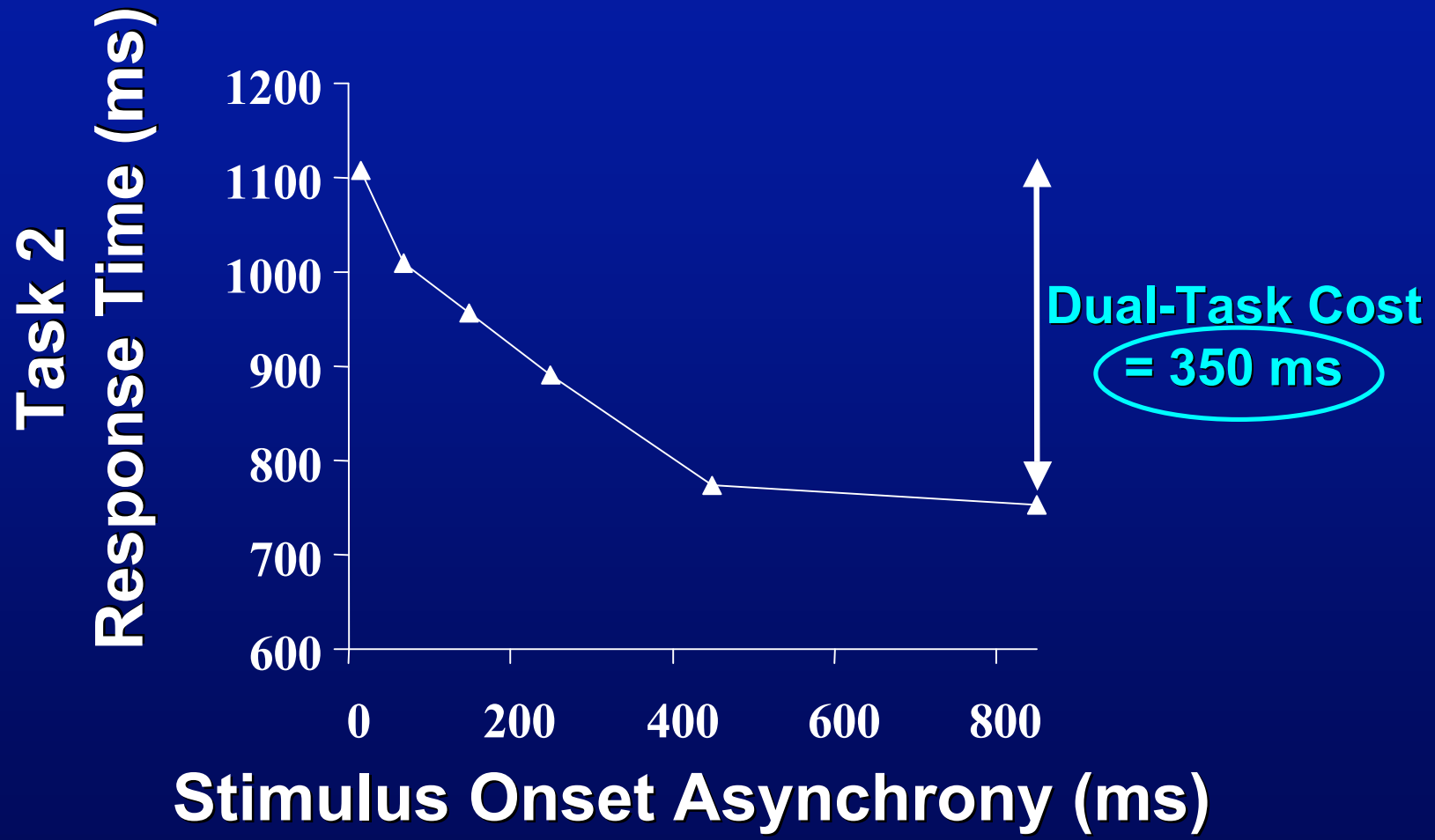
- Does practice allow people to bypass the central bottleneck?
- Many early dual-task studies found relatively little benefit of practice
- However, these studies had required manual responses to both tasks
- We decided conduct our own practice study, but with different output modalities for the two tasks (Van Selst, Ruthruff, & Johnston, 1999)

Design

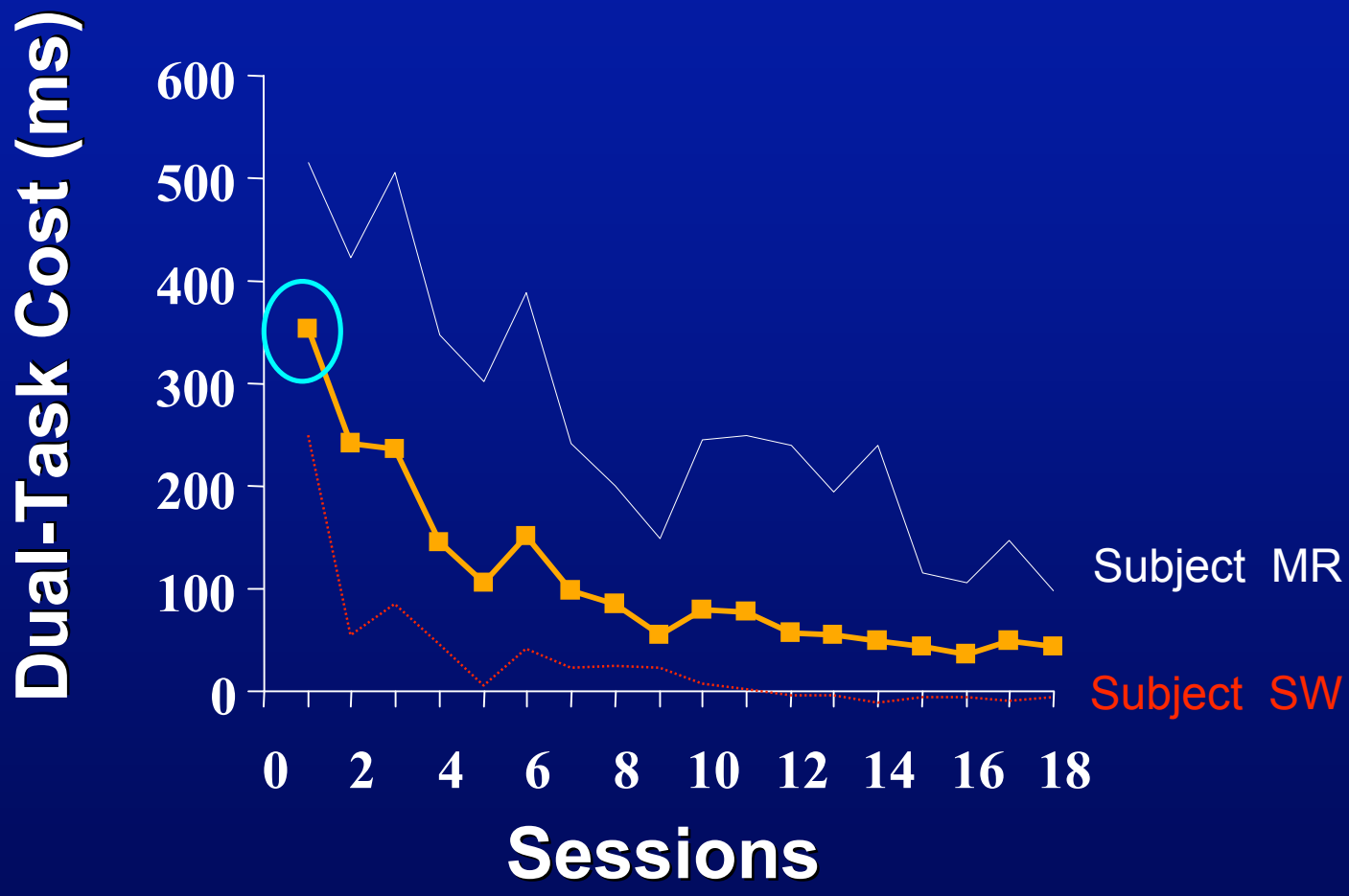
- Six subjects
- Standard dual-task paradigm
  - Task 1: Say “low” or “high” to low/high Tones
  - Task 2: Press key assigned to letters/numbers
- 36 training sessions (30 minutes each)

  Total # of trials > 14,000

Before Practice (Sessions 1)



Dual-Task Costs across Sessions



Summary

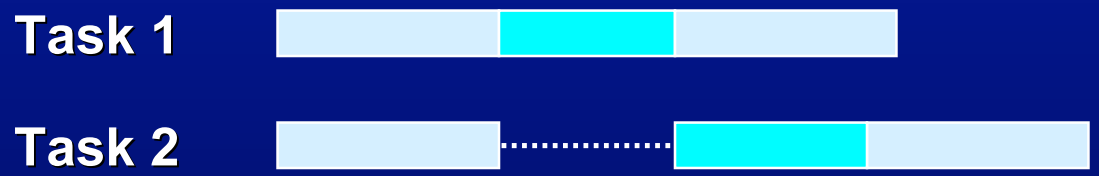
- Practice dramatically reduced the dual-task costs
  - Overturns conclusions of previous studies
  - The key is eliminating response conflicts
    - Conducted manual-manual control experiment
    - Large dual-task costs (200 ms), despite practice
- Residual dual-task costs for 5 of 6 subjects
  - Due to a processing bottleneck?

Cause of Reduction in Dual-Task Interference

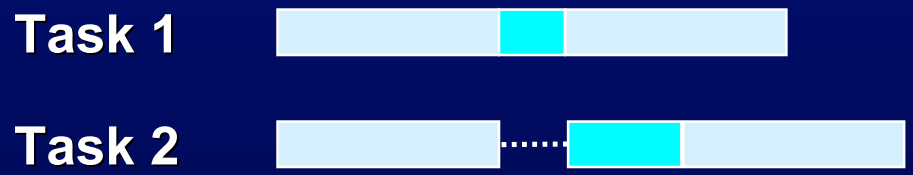
- Two possibilities
  - Practice eliminates the bottleneck
  - Practice does not eliminate the bottleneck, but does shorten stage durations

Bottleneck Model with Stage-Shortening

Early Sessions

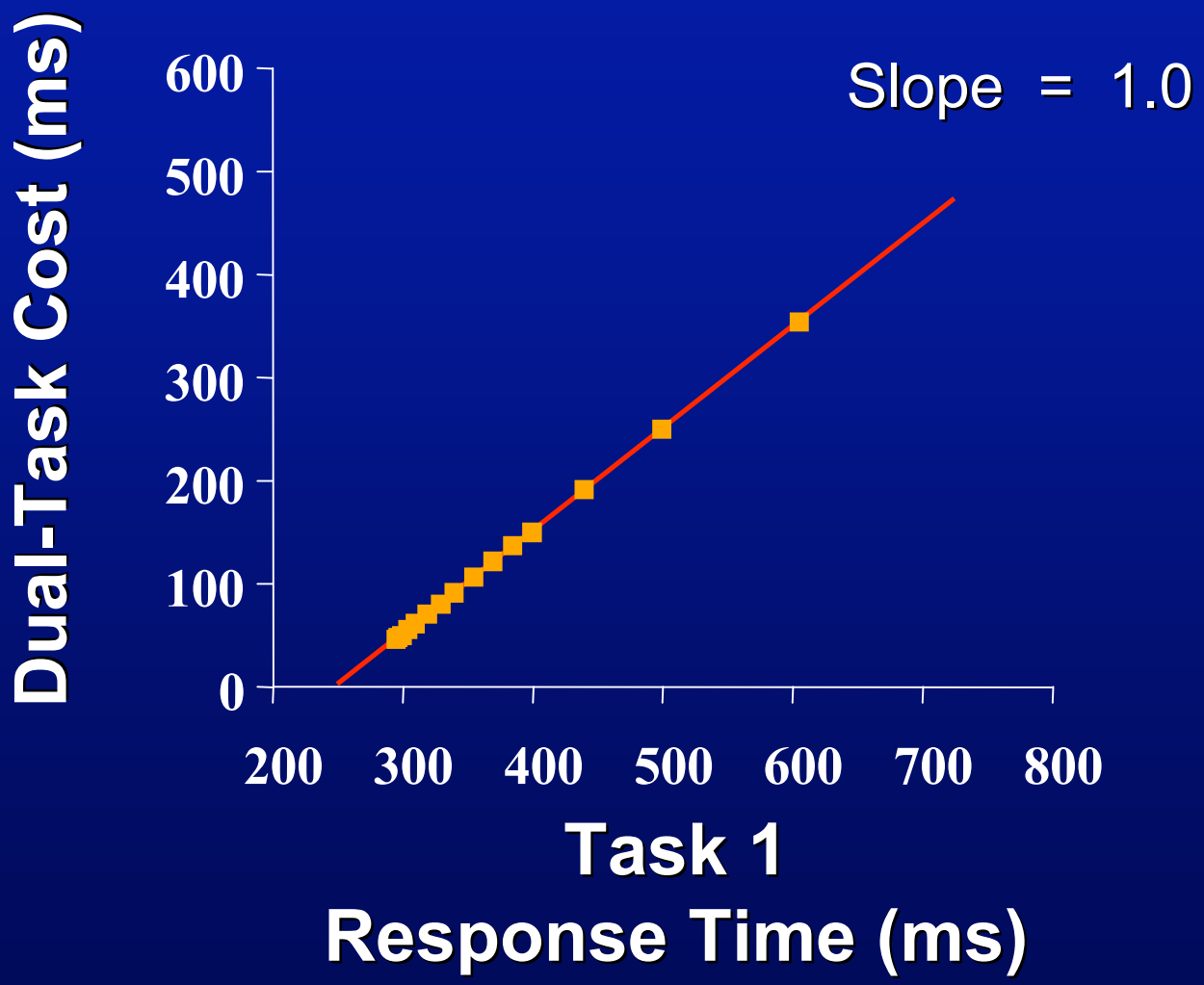


Middle Sessions

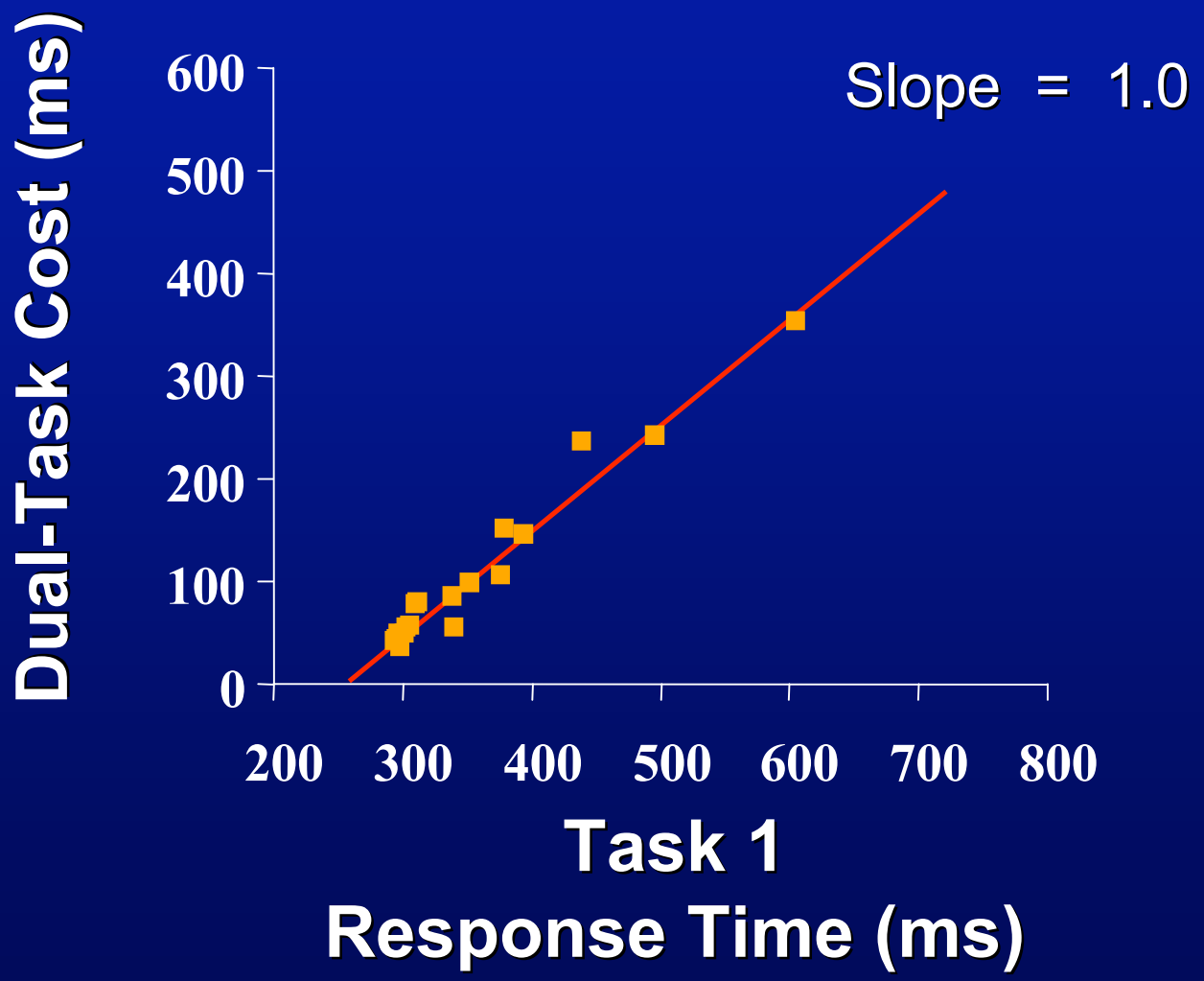


Late Sessions

Dual-Task Costs versus RT1 (Predicted)



Dual-Task Costs versus RT1



Summary

- Data support bottleneck model w/ stage-shortening
  - Bottleneck exists before and after practice
  - Practice primarily shortens central stages
- The bottleneck is stubborn – resistant even to heroic practice levels
- Is the bottleneck “immutable”?
  - No
  - Work in progress
    - Bottleneck bypass is possible
    - Requires combination of favorable conditions

Forms of Practice

- What forms of practice are needed to reduce dual-task interference?
  - Is dual-task practice necessary?
  - Or is single-task practice is sufficient?
- Bottleneck model w/ stage-shortening predicts that single-task practice on Task 1 should be sufficient
- We have confirmed this prediction (Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Van Selst, Johnston, & Remington, 2004)
- Suggests that part-task training can be very effective

Part III: Task Design

- When designing a user interface, we often have flexibility in how information is presented and how responses are made
- How can we design tasks that minimize mental workload and prevent human error?

Pairings of Input and Output Modalities

- Hypothesis: Dual-task performance is best when input and output modalities are linked to a common representational format (Wickens, Sandry & Vidulich, 1983)
  - Manual responses to visual stimuli (spatial)
  - Vocal responses to auditory stimuli (sound)
- Previous studies
  - Some tested single-task effects but not dual-task effects
  - Dual-task studies confounded modality pairings with stimulus-response compatibility

Pairings of Input and Output Modalities

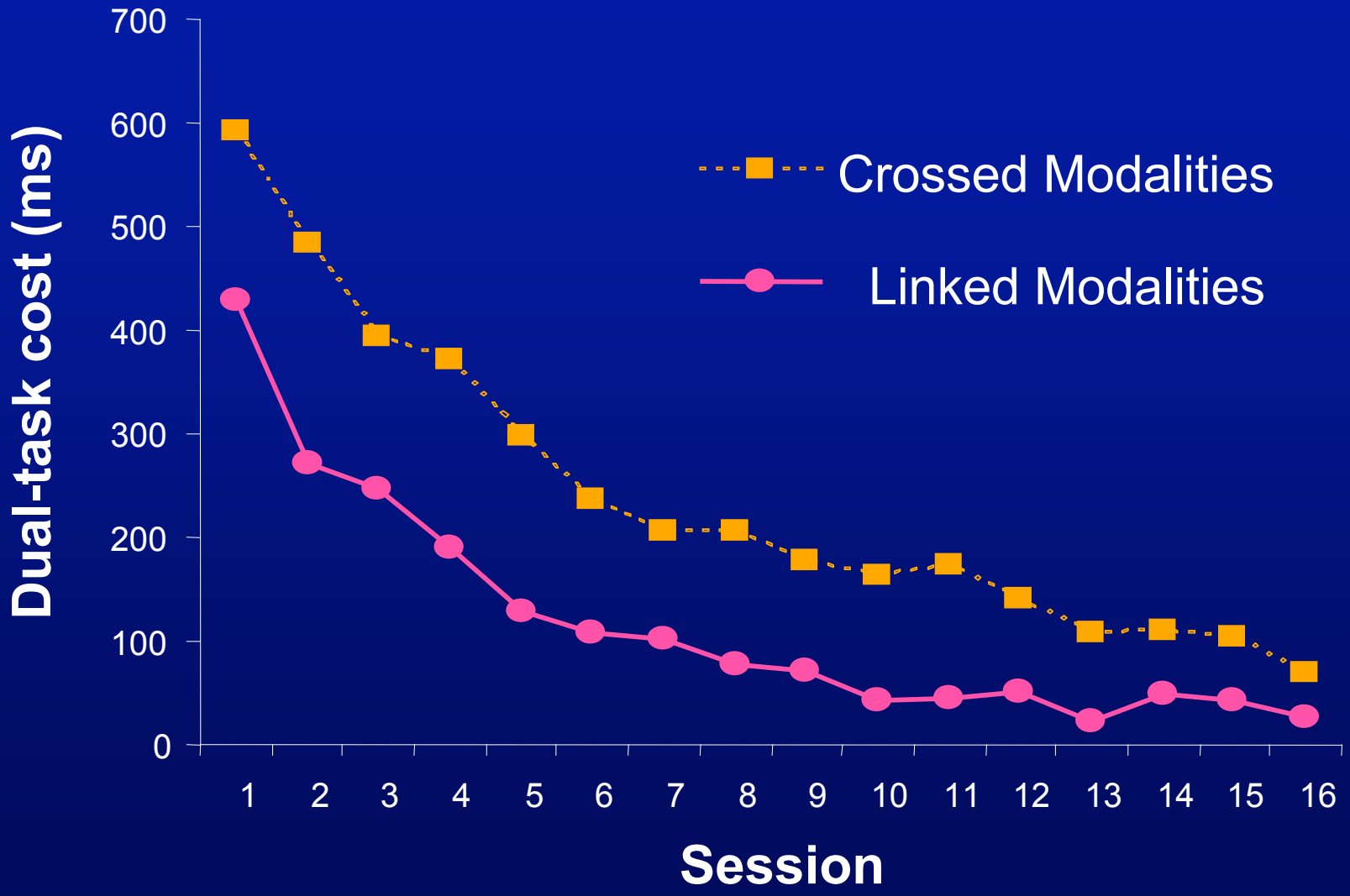
Stimuli	*Responses*
Auditory tones (low, med, high)	Vocal
Visual words (bug, food, or tree)	Manual

- Linked modality pairings
  - Vocal response (one, two, three) to tone pitch
  - Manual response (left, middle, right key) to word category
- Crossed modality pairings
  - Vocal response (“bug”, “food”, “tree”) to word category
  - Manual response (left, middle, right key) to tone pitch

Experimental Design

- Two groups of subjects
  - Linked modality pairings
  - Crossed modality pairings
- Modified dual-task design
  - Single-task blocks
  - Multi-task blocks
    - Mixture of single-task trials and dual-task trials
    - Dual-task trials used simultaneous task presentation
- To see if modality pairing effects persist with practice, participants completed 16 sessions

Results


Dual-task cost (ms)
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Session
Crossed Modalities
Linked Modalities

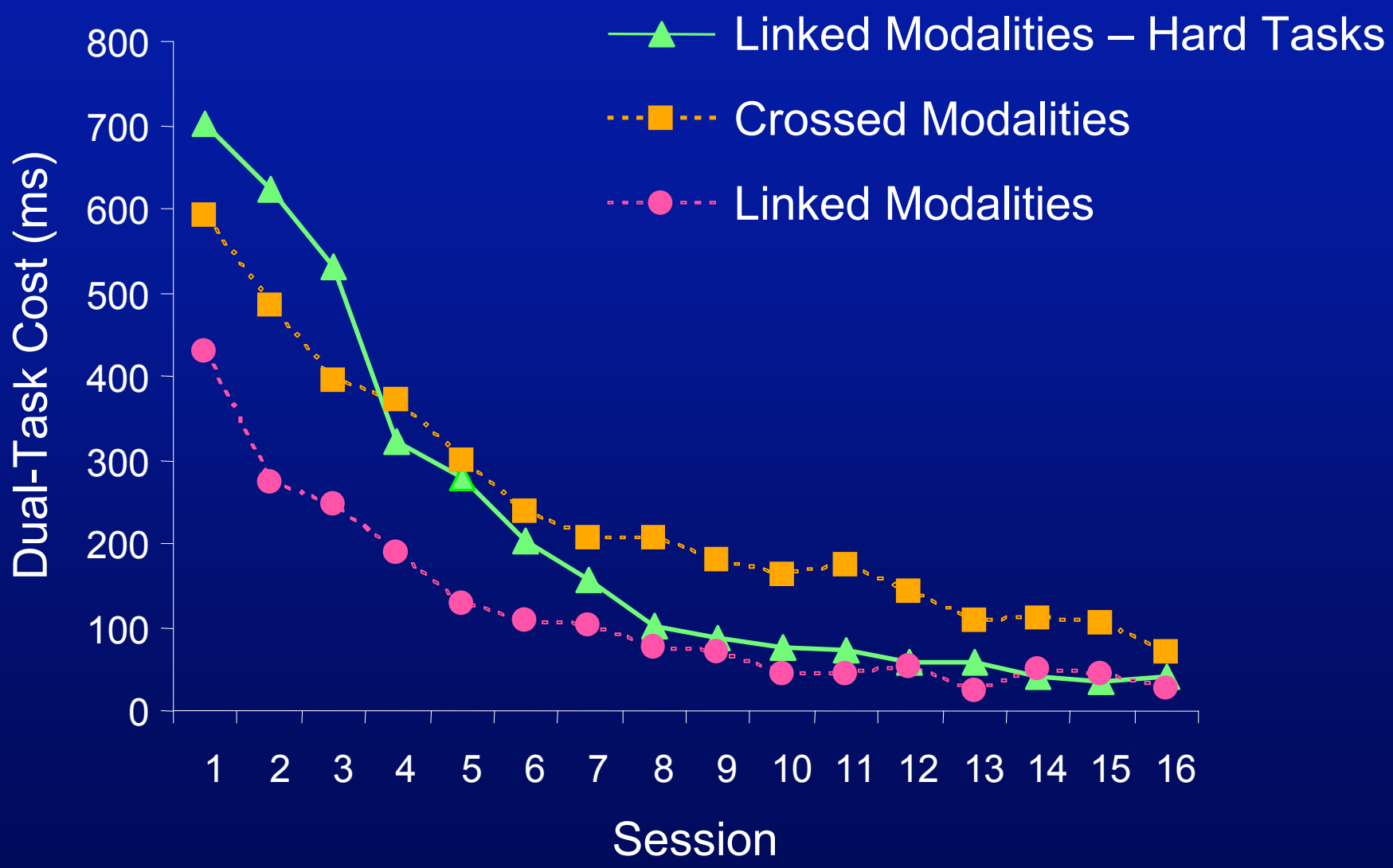
Findings

- Modality pairings strongly influence dual-task costs
- Rule of thumb: To reach a given level of dual-task performance, Crossed pairings require twice as much practice as Linked pairings

Follow-up Experiment

- Linked modalities made the tasks easier in single-task conditions
  - Is this why dual-task performance improved?
  - Or do linked modalities directly improve dual-task efficiency?
- Increased task difficulty for Linked pairings
  - More complicated auditory stimuli (tone, trill, chirp)
  - Arbitrary mapping of sounds to responses (fik, dap, goot)
- These difficult tasks produced long single-task response times (longer than crossed pairings)
- Do linked pairings still yield small dual-task costs?

Results


Linked Modalities – Hard Tasks
Crossed Modalities
Linked Modalities
Dual-Task Cost (ms)
800
700
600
500
400
300
200
100
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Session

Modality Pairing Findings

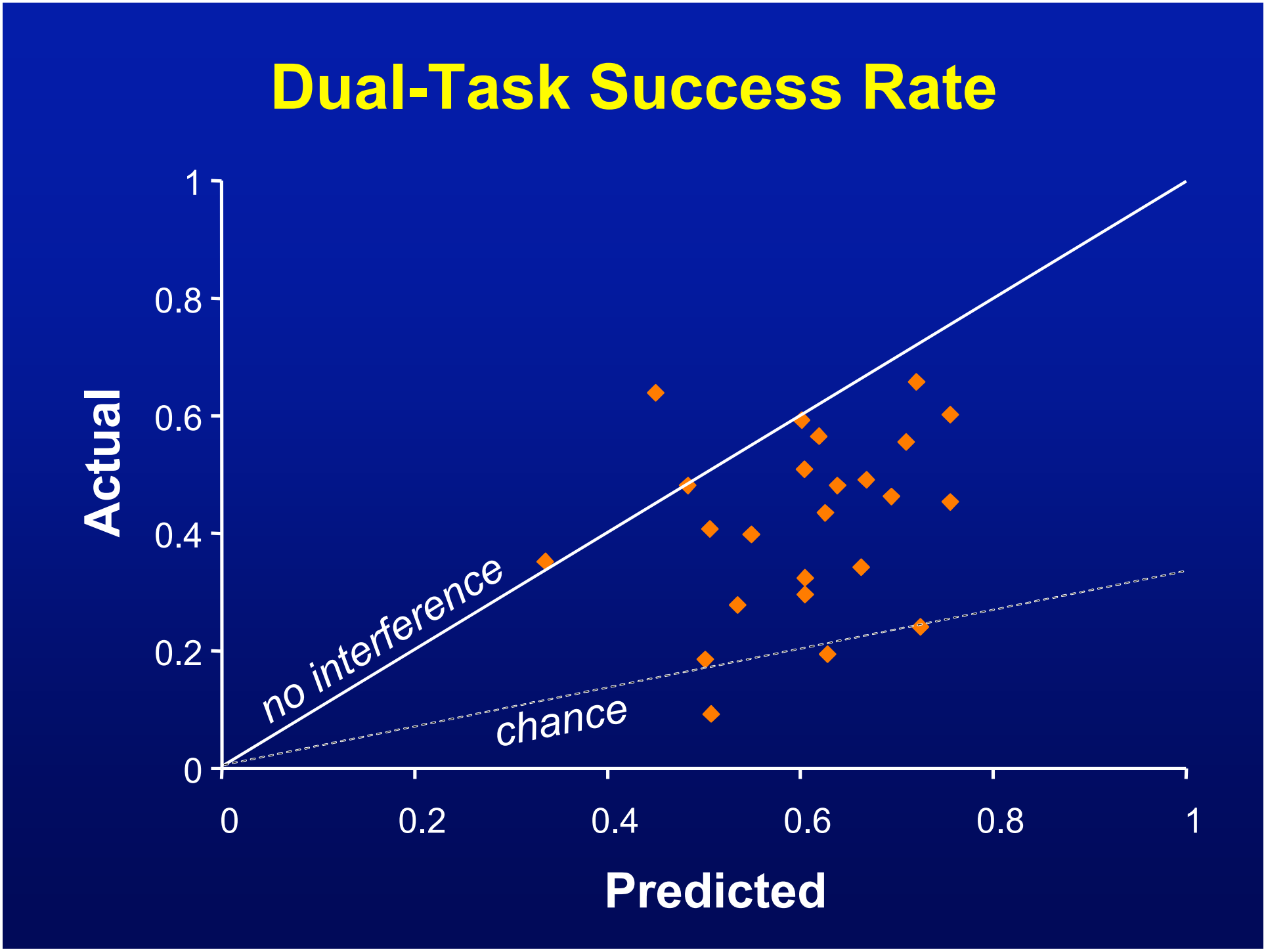
- Even when linked modality pairings produce worse single-task performance than crossed modality pairings, they produce better dual-task performance
- Linked modality pairings increase the efficiency of dual-task performance
- Based on our research, linked modality pairings proposed for user interface of crew exploration vehicle
  - Real-time mission control not possible from Earth to Mars
  - Imposes enormous workload on Mars crew
  - Critical to design user interface that suits the astronauts

Summary

- Central bottleneck plays critical role in dual-task costs
- How can the bottleneck be eliminated or ameliorated?
  - No evidence that greater effort leads to bottleneck bypass
  - Practice does not necessarily eliminate the bottleneck, but it can dramatically reduce interference
  - Linked modalities can also minimize dual-task costs

Positive Recommendations

- Efficient human multi-tasking in NASA missions can be enabled by
  - Providing practice
    - Overtraining (thousands of trials need to defeat bottleneck)
    - Single-task practice is effective
    - Dual-task practice not essential
  - Avoiding modality conflicts (e.g., multiple manual responses)
  - Using linked rather than crossed modality pairings
- Further research needed
  - Better define boundary conditions for this advice
  - Verify that these findings generalize to applied settings


Dual-Task Success Rate
Actual
Predicted
0
0.2
0.4
0.6
0.8
1
no interference
chance